MOVING COIL TYPE PLANAR MOTOR CONTROL

FIELD OF THE INVENTION

The invention relates to planar motors. More particularly, the invention is related to a control system for a moving coil type planar motor.

BACKGROUND OF THE INVENTION

Precision systems, such as those used in semiconductor processing, inspection and testing, often use linear motors for positioning objects such as semiconductor wafers. Conventional precision systems include separate, stacked stages that permit movement along perpendicular axes (*i.e.*, an "X" stage stacked on a "Y" stage). These systems typically are complex, heavy and inefficient in operation. Improved object positioning, particularly for use in lithographic instruments, has been realized through the use of planar motors, which advantageously permit simplicity in design, weight savings, as well as enhanced precision and efficiency. Such a linear or planar motor, in principle, operates in accordance with the Lorentz law, which relates the force on a charged particle to its motion in an electromagnetic field. An object such as a stage in a lithography system may be translated or propelled using the electromagnetic force generated by a wire or coil carrying an electric current in a magnetic field. The planar motor provides a single stage to replace conventional stacked stages, with the stage being electromagnetically suspended or levitated for enhanced performance and versatility.

Planar motors typically include a magnet array and a coil array. Several basic designs for planar motors are known, and are distinguished based on which of the components are positionally fixed and which move with respect thereto. In a first design, commonly referred to as a "moving coil type" planar motor, the coil array moves with respect to a positionally fixed magnet array. In one embodiment, as disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in **Fig. 1**, a moving coil planar motor **100** includes a base **102** with a flat magnet array **103** having a plurality of magnets **104**. A single X coil **106** and two Y Coils **108, 110** are attached to the underside of a stage frame **112** (drawn in dashed lines) suspended above and parallel to magnet array **102**. Y coils **108, 110** are similar in structure to one another and have coil wires oriented to provide force substantially in a Y direction. X coil **106** and Y coils **108, 110** are similar in structure, but X coil **106** has coil wires oriented to provide force substantially in an X direction perpendicular to the Y direction.

X coil **106** and Y coils **108, 110** permit movement of stage frame **112**. To provide force to stage frame **112** in the X direction relative to magnet array **102**, two phase, three phase, or multiphase commutated electric current is supplied to X coil **106** in a conventional manner by a commutation circuit and current source **114**. To provide force to stage frame **112** in the Y direction, two phase, three phase, or multiphase commutated electric current is supplied to either one or both of the Y coils **108, 110** in a conventional manner by respective commutation circuits and current sources **116** and/or **118**. To provide rotational torque to frame **112** relative to magnet array **102** in a horizontal plane parallel to the X and Y axes, commutated electric current is supplied to either of Y coils **108, 110** individually by respective commutation circuits and current source **116** or **118**. Alternatively, electric current is supplied to both Y coils **108, 110** simultaneously but with opposite polarities by respective commutation circuits and current sources **116, 118**, providing Y force to one of Y coils **108, 110** in one direction and the other Y coil **108, 110** in an opposite direction, thereby generating a torque about an axis normal to the XY plane. This torque typically causes rotation of stage frame **112** in the XY plane.

In a second design, also disclosed in U.S. Patent No. 6,097,114 to Hazelton and shown schematically in **Fig. 2**, a "moving magnet type" planar motor includes a magnet array that moves with respect to a positionally fixed coil array. In one embodiment, moving magnet planar motor **200** includes an upper surface of a flat base **202** that is covered with coil units **204**. A positioning stage **206** is suspended above flat base **202** and has an array of magnets **208** facing the upper surface of flat base **202**. A conventional commutation circuit (not shown) controls and supplies electric current to coil units **204** in accordance with the desired direction of travel of positioning stage **206**. Appropriately commutated electric current creates Lorentz forces, which propel positioning stage **206** to a desired location, altitude, and attitude.

Suspension of a stage **112, 206** may be accomplished using a variety of techniques. For example, additional, permanent magnets may be provided on the upper surface of a stage **112, 206** and on a stationary frame located above the stage **112, 206** (not shown). Alternatively, an air bearing may be provided between a stage **112, 206** and its respective base **102, 202**. Electromagnetic force generated by the motor may instead provide the necessary suspension force.

As described above, two phase, three phase, or multiphase commutated electric current may be supplied to the coils through a commutation circuit. To this end, a drawback inherent to moving magnet type planar motors is that each phase for each coil unit is driven by a separate amplifier of a commutation circuit. Experimentally, it has been

found that the required number of amplifiers is a function of the stage size; if the stage size is increased, the number of amplifiers necessary for the commutation circuit proportionally increases. For example, to drive a 5×5 moving magnet array, a suitable commutation current is generated in accordance with a four-phase motor commutation equation. In such a motor, there is a phase difference of $\pi/2$ radians between each phase, and as a result, each coil must be driven by a separate amplifier. Consequently, the array of 25 coils requires 25 amplifiers. Thus, there is a need for a planar motor control with a decreased number of amplifiers as compared to the requirements of moving magnet type planar motors.

In some magnet arrays, half magnets and/or quarter magnets are provided along the perimeter of the array to optimize the efficiency with respect to providing magnetic flux. Without the perimeter of half and/or quarter magnets, the perimeter may consist of sides of magnet segments with one pole (north or south) having no coupled nearest neighbor magnet segments of the other pole, and therefore the array may not efficiently provide magnetic flux. In addition, magnets may be provided in various shapes and sizes. Typically, magnet edge effect treatment is required, and thus there is a need for a planar motor control that obviates the need for significant magnet edge effect treatment.

In order to achieve smooth operation of planar motors, rigorous computational power must be provided. For example, complex mathematical relationships must be evaluated to achieve the desired torque and translation in the X and Y directions. To this end, significant CPU power typically is required. A need exists, therefore, for planar motor control using relationships with less complexity. In addition, certain commutation produces a motor force ripple, and thus, there further exists a need for a planar motor control with minimized force ripple.

Also, there is a need for a planar motor control that does not require a switch function in order to achieve a desired torque at any given stage location.

SUMMARY OF THE INVENTION

The present invention is related to a planar motor including a magnet array having a plurality of magnets, a coil array having a plurality of coils, and a control system configured to selectively provide electric current to the coil array for translational movement in two degrees of freedom and rotation in a third degree of freedom. The current is controlled to at least substantially reduce torque ripple in the movement. In a preferred embodiment, a coil array according to the invention is square and includes sixteen coils, and the commutation circuit comprises one amplifier for each coil. The magnet array is preferably disposed about a magnet plane and the translational movement occurs in

directions substantially parallel to the magnet plane with the directions being substantially orthogonal to one another. The directions may be the x-direction and y-direction, with a plurality of coils disposed parallel to the x-direction defining a row and a plurality of coils disposed parallel to the y-direction defining a column. The coils in each row and each column may produce a torque that follows the relationship $12I_t k_a$, wherein I_t is the current and k_a is the magnetic force constant of a coil. The current supplied to the coil array for translational movement may follow the relationship $\frac{F_n}{4k_a}$, wherein F_n is the component of force in the x-direction or the y-direction. In addition, the current supplied to the coil array for torque may follow the relationship $\frac{Torque_n}{12k_a}$, wherein $Torque_n$ is the component of torque from one or more coils in a x-direction or a y-direction. The control system compensates for undesired torque, which may be a sinusoidal function that is compensated by a negative of the sinusoidal function. Current applied to the coil array produces a force for the translational movement that is a function of the product of the current and a force constant, and produces a torque that is a function of the product of the current and a force constant.

A preferred embodiment of the present invention also is related to lithographic instruments, including a positioning stage, a planar magnet array, a planar coil array coupled to the positioning stage, and a control system configured to selectively provide electric current to the coil array for translational movement in two degrees of freedom and rotation in a third degree of freedom, with the current being controlled to at least substantially reduce force and torque ripple in the movement.

The present invention further is related to a method for controlling a planar motor for positioning in three degrees of freedom. The method includes: positioning a movable coil array over a fixed magnet array, the coil array having coils generally disposed in a plane defining first and second directions that are substantially orthogonal to one another, and the magnet array having magnets with magnetic fields; determining currents to be applied to coils to generate substantially ripple free translational forces between the coil array and the magnet array in the first and second directions and substantially ripple free torque about a third direction perpendicular to the plane; and applying currents as determined to the coils to move the coils. The determining currents may include determining compensating currents required to compensate for undesired torque, and the

undesired torque may be a sinusoidal function with the compensating currents being the negative of the sinusoidal function. The undesired torque may follow the relationship $-12k_a I_x \sin\left(\pi pt_y\right)$, wherein I_x is the current and pt_y is the pitch.

An embodiment of the present invention also relates to a system for controlling a planar motor, the motor including an array of coils for producing translational forces in two degrees of freedom. The system includes a controller, a sensor for sensing position of the coils, a first comparator for receiving position feedback from the sensor, and a second comparator for receiving input from a position disturbance in a third degree of freedom. The controller at least substantially applies a compensation function to the position disturbance and provides a corrected output position. The controller may include at least two amplifiers.

In addition, the present invention relates to a planar motor comprising magnet array means, coil array means, and control means providing electric current to said coil array means for controlled movement in three degrees of freedom including means for at least substantially eliminating ripple.

Furthermore, the present invention is related to a stage system including a planar motor, the planar motor including a magnet array having a plurality of magnets, a coil array having a plurality of coils, and a control system configured to selectively provide electric current to the coil array for translational movement in two degrees of freedom and rotation in a third degree of freedom, with the current being controlled to at least substantially reduce force and torque ripple in the movement.

The present invention also is related to an exposure apparatus including an illumination system that supplies radiant energy. The exposure apparatus also has a stage system including a planar motor, the planar motor including a magnet array having a plurality of magnets, a coil array having a plurality of coils, and a control system configured to selectively provide electric current to the coil array for translational movement in two degrees of freedom and rotation in a third degree of freedom, with the current being controlled to at least substantially reduce force and torque ripple in the movement. The stage system carries at least one object disposed on a path of the radiant energy. A device can be manufactured with the exposure apparatus. Any of a variety of devices such as semiconductor chips (*e.g.*, integrated circuits or large-scale integrations), liquid crystal panels, CCDs, thin film magnetic heads, or micro-machines, can be manufactured with the exposure apparatus.

The present invention additionally is related to a wafer including an image, wherein the image is formed with an exposure apparatus that includes: an illumination system that supplies radiant energy; and a stage system including a planar motor, the planar motor including a magnet array having a plurality of magnets, a coil array having a plurality of coils, and a control system configured to selectively provide electric current to the coil array for translational movement in two degrees of freedom and rotation in a third degree of freedom, the current being controlled to at least substantially reduce force and torque ripple in the movement. The stage system carries at least one object disposed on a path of the radiant energy.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred features of the present invention are disclosed in the accompanying drawings, wherein similar reference characters denote similar elements throughout the several views, and wherein:

Fig. 1 is a perspective view schematically showing a prior art moving coil planar motor;

Fig. 2 is a perspective view schematically showing a prior art moving magnet planar motor;

Fig. 3 is a top view schematically showing a square moving coil planar motor according to an embodiment of the present invention disposed at an initial position with respect to the magnet array;

Fig. 4 is a perspective view of the square coil array of Fig. 3;

Fig. 5 is a top view of the square coil array of Fig. 3;

Fig. 5A is a top view schematically showing a four phase moving coil planar motor according to an embodiment of the present invention;

Fig. 5B is another top view of the four phase moving coil planar motor of Fig. 5A;

Fig. 6 is a partial top view of the square coil array of Fig. 3 with one row of coils disposed at an initial position with respect to the magnet array;

Fig. 7 is a partial top view of the square coil array of Fig. 3 with one row of coils disposed at another position with respect to the magnet array;

Fig. 8 is a top view schematically showing a square moving coil planar motor disposed at another position with respect to the magnet array;

Fig. 9 is an exemplar graph showing undesired torque behavior;

Fig. 10 is an exemplar graph showing desired translation force after torque compensation according to the present invention;

Fig. 11 is an exemplar graph showing desired yaw torque after torque compensation according to the present invention;

Fig. 12A is a block diagram showing the use of an amplifier for each coil of the present invention;

Fig. 12B is a block diagram of a position control system for a coil of the present invention;

Fig. 13 is an elevational view, partially in section, showing a lithographic apparatus incorporating a planar motor-driven positioning stage according to the present invention;

Fig. 14 is a flowchart showing the fabrication of semiconductor devices; and

Fig. 15 is a flowchart showing details of the wafer processing step of Fig. 14.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring initially to **Figs. 3-5**, a moving coil planar motor **300** is shown, and includes a base with a flat magnet array **302** having a plurality of magnets **304**. Moving coil planar motors suitable for the present invention are disclosed, for example, in U.S. Patent No. 6,097,114 to Hazelton, the content of which is hereby incorporated by reference in its entirety. Coils **306** are provided for attachment to the underside of a stage frame **312** (drawn in dashed lines) for suspension above magnet array **302**. Coils **306** form a square, flat-type coil similar to that used in moving magnet planar motor stages. In a preferred embodiment, coils **306** are disposed in a 4×4 square array about a center of gravity or origin **314**, with four coils in each column $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$, and four coils in each row $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, thus forming an array of 16 coils. As will be described shortly, such an array of coils **306** permits planar motor control in 3 degrees of freedom - x- and y- translation and z-rotation. Each magnet **304** has a length of about one pitch, p, which is defined as the length of the side of a magnet **304** as shown in **Fig. 3**. Thus, each magnet has an area of about one pitch squared (p^2). A perspective view of coils **306** is shown in **Fig. 4**. Referring to **Fig. 5**, each coil has a length 3p, as shown graphically. Coils **306** used in a moving coil planar motor **300** permit movement from -3 to +3 pitches in both the x- and y-directions. Persons of ordinary skill in the art will appreciate that the present invention may be readily adapted to control coil arrays of different dimensions based on the teachings set forth herein.

Translation forces as well as torques are controlled by the four coils in each column $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$, and the four coils in each row $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$. Translation force F_x in

the x-direction of **Fig. 5** is generated by the rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$ of coils disposed parallel to the x-direction. In addition, the coils in rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$ generate about half of the torque T_z in the z-direction, which is perpendicular to the plane of the page, and for example extends from origin **314**. Another translation force F_y in the y-direction of **Fig. 5** is generated by the columns $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{C_3}$, $\mathbf{C_4}$ of coils disposed parallel to the y-direction, which also account for the other half of the torque T_z in the z-direction.

In order to describe the benefits of the control scheme permitted by the coil array of **Figs. 3-5,** each of coils **306** are disposed about a center point **CEN** located at an (x,y) position, measured in units of pitch, along axes x, y. Each of the 16 coils may thus be identified in terms of its location in the array (row, column) and the location of its center point CEN with respect to origin **314** (x, y). Thus, the sixteen coils are initially described as follows:

$$(R_1,C_1):(-4.5,-4.5);\; (R_1,C_2):(-1.5,-4.5);\; (R_1,C_3):(+1.5,-4.5);\; (R_1,C_4):(+4.5,-4.5); \quad (1)$$
$$(R_2,C_1):(-4.5,-1.5);\; (R_2,C_2):(-1.5,-1.5);\; (R_2,C_3):(+1.5,-1.5);\; (R_2,C_4):(+4.5,-1.5); \quad (2)$$
$$(R_3,C_1):(-4.5,+1.5);\; (R_3,C_2):(-1.5,+1.5);\; (R_3,C_3):(+1.5,+1.5);\; (R_3,C_4):(+4.5,+1.5); \quad (3)$$
$$(R_4,C_1):(-4.5,+4.5);\; (R_4,C_2):(-1.5,+4.5);\; (R_4,C_3):(+1.5,+4.5);\; (R_4,C_4):(+4.5,+4.5). \quad (4)$$

Movement of each of coils **306** by +0.5 pitch along the x-axis and -0.5 pitch along the y-axis thus results in the following new positions:

$$(R_1,C_1):(-4,-5);\; (R_1,C_2):(-1,-5);\; (R_1,C_3):(+2,-5);\; (R_1,C_4):(+5,-5); \quad (5)$$
$$(R_2,C_1):(-4,-2);\; (R_2,C_2):(-1,-2);\; (R_2,C_3):(+2,-2);\; (R_2,C_4):(+5,-2); \quad (6)$$
$$(R_3,C_1):(-4,+1);\; (R_3,C_2):(-1,+1);\; (R_3,C_3):(+2,+1);\; (R_3,C_4):(+5,+1); \quad (7)$$
$$(R_4,C_1):(-4,+4);\; (R_4,C_2):(-1,+4);\; (R_4,C_3):(+2,+4);\; (R_4,C_4):(+5,+4). \quad (8)$$

With these positions, the magnet force constant, k_m, that is located under a group of coils is determined for the coils in rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$ as follows:

$$\text{For } R_1:\; k_{m_{ni}} := k_m\left(pt_{x(n_i)}, pt_{y(n_i)} - 5\right); \quad (9)$$
$$\text{For } R_2:\; k_{m_{ni}} := k_m\left(pt_{x(n_i)}, pt_{y(n_i)} - 2\right); \quad (10)$$
$$\text{For } R_3:\; k_{m_{ni}} := k_m\left(pt_{x(n_i)}, pt_{y(n_i)} + 1\right); \quad (11)$$
$$\text{For } R_4:\; k_{m_{ni}} := k_m\left(pt_{x(n_i)}, pt_{y(n_i)} + 4\right). \quad (12)$$

here $pt_{x(n_i)}$ and $pt_{y(n_i)}$ are the number of pitch of each of the four coils in the row in the x- and y- directions, respectively.

In particular, using row $\mathbf{R_3}$ as the starting row for these calculations, the magnetic force constant for rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_4}$ may be determined by accounting for the offset distance value between row $\mathbf{R_3}$ and the desired row $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_4}$. Thus, the magnet force constant located under row $\mathbf{R_1}$ is calculated by noting that the offset distance in the y-direction between the center points **CEN** of a coil in row $\mathbf{R_3}$ and a coil in row $\mathbf{R_1}$ is 6 pitches. This is due to the fact that the distance in the y-direction from the center points **CEN** of a coil in row $\mathbf{R_3}$ and a coil in row $\mathbf{R_1}$ is -6 pitches. The distances of rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_4}$ from row $\mathbf{R_3}$ are -6 pitches, -3 pitches, and +3 pitches, respectively.

The magnetic force constant located under each of the moving coils in row $\mathbf{R_3}$ is described by the following matrices:

$$\text{For } (\mathrm{R}_3, C_1):\quad k_m(x_1, y_1) := \begin{bmatrix} k_x \cos\left(x_1 \frac{\pi}{2} - 4.5\frac{\pi}{2}\right)\sin\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ k_y \sin\left(x_1 \frac{\pi}{2} - 4.5\frac{\pi}{2}\right)\cos\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ 0 \end{bmatrix} \tag{13}$$

$$\text{For } (\mathrm{R}_3, C_2):\quad k_m(x_1, y_1) := \begin{bmatrix} k_x \cos\left(x_1 \frac{\pi}{2} - 1.5\frac{\pi}{2}\right)\sin\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ k_y \sin\left(x_1 \frac{\pi}{2} - 1.5\frac{\pi}{2}\right)\cos\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ 0 \end{bmatrix} \tag{14}$$

$$\text{For } (\mathrm{R}_3, C_3):\quad k_m(x_1, y_1) := \begin{bmatrix} k_x \cos\left(x_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right)\sin\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ k_y \sin\left(x_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right)\cos\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ 0 \end{bmatrix} \tag{15}$$

$$\text{For } (\mathrm{R}_3, C_4):\quad k_m(x_1, y_1) := \begin{bmatrix} k_x \cos\left(x_1 \frac{\pi}{2} + 4.5\frac{\pi}{2}\right)\sin\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ k_y \sin\left(x_1 \frac{\pi}{2} + 4.5\frac{\pi}{2}\right)\cos\left(y_1 \frac{\pi}{2} + 1.5\frac{\pi}{2}\right) \\ 0 \end{bmatrix} \tag{16}$$

Equations 13-16 may be modified to describe the coils in rows $\mathbf{R_1}$,$\mathbf{R_2}$,$\mathbf{R_4}$ by accounting for the offset distance from row $\mathbf{R_3}$, as presented in equations 5-8, and thus the magnetic force constant for the moving coil planar motor **300** may be determined.

Similar to a moving magnet planar motor, commutation of the exemplar moving coil planar motor can be analyzed with 4-phase linear motor equations. As shown in **Fig. 5A**, a four-phase motor includes four coils **306a, 306b, 306c, 306d,** as well as one row of magnets **304** each separated by a distance of one pitch, corresponding to a phase difference φ of π/2 radians between phases. In this arrangement of coils **306a, 306b, 306c,**

306d and magnets **304**, one degree of freedom is provided, along the x-axis. The magnet force constant for coils **306a, 306b, 306c, 306d** is determined as follows:

$$
\begin{aligned}
k_x(\text{pitch}) &= k_x \sin(\text{pitch} + \phi) && (17)\\
&= k_x \sin(x + 0) && \text{(coil 306a)}\\
&= k_x \sin(x + \tfrac{3\pi}{2}) && \text{(coil 306b)}\\
&= k_x \sin(x + \tfrac{6\pi}{2}) && \text{(coil 306c)}\\
&= k_x \sin(x + \tfrac{9\pi}{2}) && \text{(coil 306d)}\\
&= k_x \sin(x) - k_x \cos(x) - k_x \sin(x) - k_x \cos(x)
\end{aligned}
$$

The commutation current associated with each of coils **306a, 306b, 306c, 306d** is found as:

$$
\begin{aligned}
I_x(\text{pitch}) &= I_x \sin(\text{pitch} + \phi) && (18)\\
&= I_x \sin(x + 0) && \text{(coil 306a)}\\
&= I_x \sin(x + \tfrac{3\pi}{2}) && \text{(coil 306b)}\\
&= I_x \sin(x + \tfrac{6\pi}{2}) && \text{(coil 306c)}\\
&= I_x \sin(x + \tfrac{9\pi}{2}) && \text{(coil 306d)}\\
&= I_x \sin(x) - I_x \cos(x) - I_x \sin(x) - I_x \cos(x)
\end{aligned}
$$

Using the four phase magnet force constant, four phase commutation produces a constant force regardless of stage position:

$$
\begin{aligned}
F &= k_x I_x \sin(x)\sin(x) + k_x I_x \cos(x)\cos(x) + && (19)\\
&\quad k_x I_x \sin(x)\sin(x) + k_x I_x \cos(x)\cos(x)\\
&= k_x I_x \sin^2(x) + k_x I_x \cos^2(x) +\\
&\quad k_x I_x \sin^2(x) + k_x I_x \cos^2(x)\\
&= 2k_x I_x
\end{aligned}
$$

Next, an arrangement of coils **306a, 306b, 306c, 306d** and magnets **304** for providing two degrees of freedom, along the x- and y- axes, is shown in **Fig. 5B**. In this instance, the magnet force constant for coils **306a, 306b, 306c, 306d** is determined as follows:

$$k_{xy}(pitch_x, pitch_y) = k_{xy}\sin(x+0)\cos(y) \quad \text{(coil 306a)} \quad (20)$$
$$= k_{xy}\sin(x+\tfrac{3\pi}{2})\cos(y) \quad \text{(coil 306b)}$$
$$= k_{xy}\sin(x+\tfrac{6\pi}{2})\cos(y) \quad \text{(coil 306c)}$$
$$= k_{xy}\sin(x+\tfrac{9\pi}{2})\cos(y) \quad \text{(coil 306d)}$$

Again, the commutation current associated with each of coils **306a, 306b, 306c, 306d** is found as:

$$I_{xy}(pitch_x, pitch_y) = I_{xy}\sin(x+0)\cos(y) \quad \text{(coil 306a)} \quad (21)$$
$$= I_{xy}\sin(x+\tfrac{3\pi}{2})\cos(y) \quad \text{(coil 306b)}$$
$$= I_{xy}\sin(x+\tfrac{6\pi}{2})\cos(y) \quad \text{(coil 306c)}$$
$$= I_{xy}\sin(x+\tfrac{9\pi}{2})\cos(y) \quad \text{(coil 306d)}$$

Similarly, four phase commutation for two degrees of freedom produces a constant force regardless of stage position:

$$\begin{aligned} F &= k_{xy}I_{xy}\sin(x)\sin(x)\cos^2(y) + k_{xy}I_{xy}\cos(x)\cos(x)\cos^2(y) + \\ &\quad + k_{xy}I_{xy}\sin(x)\sin(x)\cos^2(y) + k_{xy}I_{xy}\cos(x)\cos(x)\cos^2(y) \\ &= 2k_{xy}I_{xy}[\sin^2(x)+\cos^2(x)]\cos^2(y) \\ &= 2k_{xy}I_{xy}\cos^2(y) \end{aligned} \quad (22)$$

Following the aforementioned approach incorporating the four phase motor equation, commutation with one degree of freedom again may be analyzed for a group of coils **306**, shown in a different position in **Fig. 6**, to further demonstrate the creation of a constant translation force at a given position. In particular, it is noted that in this construction, the center points **CEN** of coils **306** in row $\mathbf{R_3}$ are offset in the y-direction by a distance 1.5 pitch (1.5p) from the x-axis through origin **314**. The magnet force constant in the x-direction for row $\mathbf{R_3}$ is represented by the first row of each of the matrices in equations 13-16. Also, the coil **306** located at position (R_3, C_3) is offset in the x-direction by a distance 1.5 pitch (1.5p) from the y-axis through origin **314**, while the offsets for the other coils do not fall at a whole number of pitch. For the purposes of this exemplar analysis, non-whole number offsets, present in both the x- and y-directions, unnecessarily complicate the explanation due to the sine and cosine behavior, and thus it is desirable to present an

analysis with coils **306** whose center points **CEN** are located in both the x- and y-directions at a whole number of pitch.

Turning to **Fig. 7**, in order to demonstrate commutation of the exemplar moving coil planar motor **300**, coils **306** in row $\mathbf{R_3}$ have been moved such that their center points **CEN** are offset in the y-direction by a distance 1.0 pitch (1.0p) from the x-axis through origin **314**. In addition, the coil **306** located at position (R_3, C_3) has been moved to an offset in the x-direction by a distance 2.0 pitch (2.0p) from the y-axis through origin **314**, with the offsets for the other coils **306** also set at a whole number of pitch. With this new alignment, the magnet force constants in the x-direction for coils **306** in row $\mathbf{R_3}$ are as follows:

$$\text{For } (R_3,C_1)\text{:}\quad k_m(x_1) = k_{xy}\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) = k_{xy}\cos(x)\cos(y); \tag{23}$$

$$\text{For } (R_3,C_2)\text{:}\quad k_m(x_1) = k_{xy}\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) = k_{xy}\sin(x)\cos(y); \tag{24}$$

$$\text{For } (R_3,C_3)\text{:}\quad k_m(x_1) = k_{xy}\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) = -k_{xy}\cos(x)\cos(y); \tag{25}$$

$$\text{For } (R_3,C_4)\text{:}\quad k_m(x_1) = k_{xy}\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) == -k_{xy}\sin(x)\cos(y). \tag{26}$$

A constant translation force is obtained for coils **306** by providing a physical coil current, I, and this current for each of coils **306** at positions (R_3, C_1), (R_3, C_2), (R_3, C_3), and (R_3, C_4) is:

$$I_{(R_3,C_1)} = \left[I_x\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) + I_y\cos\left(y + \tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right)\right] = I_x\cos(x)\cos(y) - I_y\sin(y)\sin(x); \tag{27}$$

$$I_{(R_3,C_2)} = \left[I_x\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) + I_y\cos\left(y + \tfrac{\pi}{2}\right)\sin\left(x - 1\tfrac{\pi}{2}\right)\right] = I_x\sin(x)\cos(y) + I_y\sin(y)\cos(x); \tag{28}$$

$$I_{(R_3,C_3)} = \left[I_x\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) + I_y\cos\left(y + \tfrac{\pi}{2}\right)\sin\left(x + 2\tfrac{\pi}{2}\right)\right] = -I_x\cos(x)\cos(y) + I_y\sin(y)\sin(x); \tag{29}$$

$$I_{(R_3,C_4)} = \left[I_x\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + \tfrac{\pi}{2}\right) + I_y\cos\left(y + \tfrac{\pi}{2}\right)\sin\left(x + 5\tfrac{\pi}{2}\right)\right] = -I_x\sin(x)\cos(y) - I_y\sin(y)\cos(x). \tag{30}$$

The translation force is the product obtained by multiplying each of the aforementioned magnet force constants by its respective commutation current. For example, in the x-direction the force for the coils in row $\mathbf{R_3}$ is found as follows:

For R_3: (31)

$$
\begin{aligned}
F_x = {} & k_{xy}\cos\left(x-4\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)\left[I_x\cos\left(x-4\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)+I_y\cos\left(y+\tfrac{\pi}{2}\right)\sin\left(x-4\tfrac{\pi}{2}\right)\right]+\\
& k_{xy}\cos\left(x-1\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)\left[I_x\cos\left(x-1\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)+I_y\cos\left(y+\tfrac{\pi}{2}\right)\sin\left(x-1\tfrac{\pi}{2}\right)\right]+\\
& k_{xy}\cos\left(x+2\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)\left[I_x\cos\left(x+2\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)+I_y\cos\left(y+\tfrac{\pi}{2}\right)\sin\left(x+2\tfrac{\pi}{2}\right)\right]+\\
& k_{xy}\cos\left(x+5\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)\left[I_x\cos\left(x+5\tfrac{\pi}{2}\right)\sin\left(y+\tfrac{\pi}{2}\right)+I_y\cos\left(y+\tfrac{\pi}{2}\right)\sin\left(x+5\tfrac{\pi}{2}\right)\right]\\
= {} & k_{xy}\cos(x)\sin(y)\left[I_x\cos(x)\cos(y)-I_y\sin(y)\sin(x)\right]+\\
& k_{xy}\sin(x)\cos(y)\left[I_x\sin(x)\cos(y)+I_y\sin(y)\cos(x)\right]+\\
& -k_{xy}\cos(x)\cos(y)\left[-I_x\cos(x)\cos(y)+I_y\sin(y)\sin(x)\right]+\\
& -k_{xy}\sin(x)\cos(y)\left[-I_x\sin(x)\cos(y)-I_y\sin(y)\cos(x)\right]\\
= {} & k_{xy}I_x\cos^2(x)\cos^2(y)-k_xI_y\cos(x)\cos(y)\sin(y)\sin(x)+\\
& k_{xy}I_x\sin^2(x)\cos^2(y)+k_xI_y\cos(x)\cos(y)\sin(y)\sin(x)+\\
& k_{xy}I_x\cos^2(x)\cos^2(y)-k_xI_y\cos(x)\cos(y)\sin(y)\sin(x)+\\
& k_{xy}I_x\sin^2(x)\cos^2(y)+k_xI_y\cos(x)\cos(y)\sin(y)\sin(x)+\\
= {} & k_{xy}I_x\cos^2(y)\left[\cos^2(x)+\sin^2(x)\right]+\\
& k_{xy}I_x\cos^2(y)\left[\cos^2(x)+\sin^2(x)\right]\\
= {} & 2I_xk_{xy}\cos^2(y)
\end{aligned}
$$

where I_x represents the x-direction control current in amperes, I_y represents the y-direction control current in amperes, and k_{xy} represents the planar magnet force constant in Newtons, ampere.

The calculation performed above may be repeated for each of coils **306** in rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, and thus the translation forces in the x-direction due to the coils **306** in each of the rows are as follows:

$$\text{For } R_1\text{:}\quad F_{x1} = 2I_xk_a\cos^2(y); \qquad (32)$$

$$\text{For } R_2\text{:}\quad F_{x2} = 2I_xk_a\sin^2(y); \qquad (33)$$

$$\text{For } R_3\text{:}\quad F_{x3} = 2I_xk_a\cos^2(y); \qquad (34)$$

$$\text{For } R_4\text{:}\quad F_{x4} = 2I_xk_a\sin^2(y). \qquad (35)$$

where force constant k_a is the same as force constant k_{xy}. The total translation force provided by the coils **306** is the summation of the translation forces provided by each of the rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$, and simplifies to:

$$F_{x_{total}} = 4I_x k_a \qquad (36)$$

The total translation force in the y-direction may also be found in the same fashion, and simplifies to:

$$F_y = 4I_y k_a \qquad (37)$$

It is desirable to provide torque or yaw control (θ_z) for the moving coil planar magnet so that control of a third degree of freedom complements the x- and y-direction translational force control already discussed. In order to calculate torque, the distance from each of the coils to the center of gravity of the coil array must be known. To this end, referring again to **Fig. 3**, it is noted that the distances between each of coils **306** are fixed. Thus, as shown in **Fig. 3**, the center points **CEN** of coils **306** in rows $\mathbf{R_1}$ and $\mathbf{R_4}$ are offset in the y-direction by distances $\mathbf{L_1}$, $\mathbf{L_4}$ of -4.5 pitch (-4.5p) and 4.5 pitch (4.5p), respectively, from the x-axis that extends through origin 314, while the center points **CEN** of coils **306** in rows $\mathbf{R_2}$ **and** $\mathbf{R_3}$ are offset by distances $\mathbf{L_2}$, $\mathbf{L_3}$ of -1.5 pitch (-1.5p) and 1.5 pitch (1.5p), respectively. To create torque, current $+I_t$ is applied to coils **306** in rows $\mathbf{R_3}$ and $\mathbf{R_4}$, while current $-I_t$ is applied to coils **306** in rows $\mathbf{R_1}$ and $\mathbf{R_2}$, such that the following torque-related translation forces are generated:

$$\text{For } R_1\text{:}\quad T_1 = L_1\left[2I_t k_a \cos^2(y)\right]; \qquad (38)$$

$$\text{For } R_2\text{:}\quad T_2 = L_2\left[2I_t k_a \sin^2(y)\right]; \qquad (39)$$

$$\text{For } R_3\text{:}\quad T_3 = L_3\left[2(-I_t)k_a \cos^2(y)\right]; \qquad (40)$$

$$\text{For } R_4\text{:}\quad T_4 = L_4\left[2(-I_t)k_a \sin^2(y)\right]. \qquad (41)$$

The y-term in Equations 38 to 41 is zero for the stage at the origin in **Fig. 3**. Next, substituting the know offset distances $\mathbf{L_1}$-$\mathbf{L_4}$ and adding torque contributions $\mathbf{T_1}$-$\mathbf{T_4}$, the total torque is found as:

$$
\begin{aligned}
\mathrm{T}_{\text{total}} &= -4.5\left[2I_t k_a \cos^2(y)\right] - 1.5\left[2I_t k_a \sin^2(y)\right] \\
&\quad + 1.5\left[2(-I_t)k_a \cos^2(y)\right] + 4.5\left[2(-I_t)k_a \sin^2(y)\right] \\
&= -3I_t k_a\left[\sin^2(y) + \cos^2(y)\right] - 9I_t k_a\left[\sin^2(y) + \cos^2(y)\right] \\
&= -12I_t k_a \qquad (42)
\end{aligned}
$$

Thus, the components of torque from the rows of coils **306** produce the following torque with units of Newton-pitch:

$$\text{torque}_{\text{row}} = 12I_{t_x}k_a \qquad (43)$$

Similarly, the components of torque from the columns of coils **306** produce the following torque with units of Newton-pitch:

$$\text{torque}_{\text{column}} = 12I_{t_y}k_a \qquad (44)$$

The force and torque expressions above can be solved to give the coil current for the x- and y- translation forces and torque, related to control in three degrees of freedom using 16 coils, as follows:

$$I_x = \frac{F_x}{4k_a}; \qquad (45)$$

$$I_y = \frac{F_y}{4k_a}; \qquad (46)$$

$$I_{t_x} = \frac{\text{Torque}}{12\mathrm{k}_\mathrm{a}} \qquad (47)$$

With the above relations established, simultaneous production of x- and y- translation forces as well as torque (θ_z) can be considered, so that the control movement for all three degrees of freedom can be determined. For an array of coils **306** as disposed in **Fig. 8**, with the stage shifted from the origin position of **Fig. 3**, the translation forces can be calculated. For example, row $\mathbf{R}_1$ of coils **306** have coordinates (-4,-5), (-1,-5), (2,-5), and (5,-5). The coordinates, along with the commutation functions for translation force and torque of coils **306** in the row (represented in brackets), are used to determine the translation force as follows:

For R_1:

$$F_x = k_x \cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 5\tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 5\tfrac{\pi}{2}\right)\sin\left(x - 1\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 5\tfrac{\pi}{2}\right)\sin\left(x + 2\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y - 5\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 5\tfrac{\pi}{2}\right)\sin\left(x + 5\tfrac{\pi}{2}\right)\end{bmatrix}$$

$$= 2I_x k_x \cos^2(y) + 2I_{t_x} k_x \cos^2(y) \qquad (48)$$

The translation forces for the remaining rows are as follows:

For R_2:

$$F_x = k_x \cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 2\tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 2\tfrac{\pi}{2}\right)\sin\left(x - 1\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 2\tfrac{\pi}{2}\right)\sin\left(x + 2\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x + I_{t_x}\right)\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y - 2\tfrac{\pi}{2}\right) + \\ \left(I_y + I_{t_y}\right)\cos\left(y - 2\tfrac{\pi}{2}\right)\sin\left(x + 5\tfrac{\pi}{2}\right)\end{bmatrix}$$

$$= 2I_x k_x \sin^2(y) + 2I_{t_x} k_x \sin^2(y) \qquad (49)$$

For R_3:

$$F_x = k_x \cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 1\tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 1\tfrac{\pi}{2}\right)\sin\left(x - 1\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 1\tfrac{\pi}{2}\right)\sin\left(x + 2\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 1\tfrac{\pi}{2}\right)\sin\left(x + 5\tfrac{\pi}{2}\right)\end{bmatrix}$$

$$= 2I_x k_x \cos^2(y) - 2I_{t_x} k_x \cos^2(y) \qquad (50)$$

For R_4:

$$F_x = k_x \cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 4\tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x - 1\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 4\tfrac{\pi}{2}\right)\sin\left(x - 1\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x + 2\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 4\tfrac{\pi}{2}\right)\sin\left(x + 2\tfrac{\pi}{2}\right)\end{bmatrix} +$$

$$k_x \cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right)\begin{bmatrix}\left(I_x - I_{t_x}\right)\cos\left(x + 5\tfrac{\pi}{2}\right)\sin\left(y + 4\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 4\tfrac{\pi}{2}\right)\sin\left(x + 5\tfrac{\pi}{2}\right)\end{bmatrix}$$

$$= 2I_x k_x \sin^2(y) - 2I_{t_x} k_x \sin^2(y) \qquad (51)$$

Once the y-direction offset distances from the center points **CEN** of coils **306** in each of rows $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$, $\mathbf{R_4}$ from the x-direction axis through the center of gravity of the array of coils **306** are established, as shown in **Fig. 8** with respect to offset distances $\mathbf{L_1}$-$\mathbf{L_4}$, the total force in the x-direction is found by summing the contributions of the forces generated by each row:

$$\begin{aligned} F_{x_{total}} &= F_{x(row1)} + F_{x(row2)} + F_{x(row3)} + F_{x(row4)} \\ &= 4\mathrm{I}_x k_a\left[\sin^2(y) + \cos^2(y)\right] \end{aligned} \tag{52}$$

The total torque is calculated as:

$$\begin{aligned} T_x &= -4.5\left[2I_{t_x}k_a\cos^2(y)\right] - 1.5\left[2I_{t_x}k_a\sin^2(y)\right] \\ &\quad -1.5\left[2I_{t_x}k_a\cos^2(y)\right] - 4.5\left[2I_{t_x}k_a\sin^2(y)\right] \\ &= -12I_{t_x}k_a\left[\sin^2(y) + \cos^2(y)\right] \end{aligned} \tag{53}$$

One problem with prior art control schemes is undesired torque in z-rotation due to current applied for x- and y-translation. Such undesirable interaction is frequently referred to as cross-coupling, which creates a ripple behavior. Referring to **Fig. 3**, if the planar motor generates a translation force in the x-direction along the x-axis (*i.e.*, an offset of 0 pitch in the y-direction), the translation force is generated symmetrically about the center of gravity of the planar motor. This is due to the equidistant spacing of the center of gravity **314** between adjacent rows of magnets **304** parallel to the x-axis. However, if coils **306** are aligned such that the center of gravity is offset in the y-direction from the x-axis (*i.e.*, in an amount of 0.5 pitch), as shown in **Fig. 8**, the translation force is no longer generated in a symmetrical fashion with respect to the center of gravity **314** and undesired torque occurs. In this instance, the center of gravity **314** is not equidistant from adjacent rows of magnets **304** parallel to the x-axis. To address this problem, torque compensation predicated on the magnitude of the translation force is implemented. The undesired torque generally follows a sinusoidal wave of a sin(x) or cos(x) function, as represented graphically in **Fig. 9** showing undesired torque (in Newton-pitch) as a function of pitch (in number of pitch), and calculated as follows:

$$T_{undesired} = -12k_aI_x\sin\left(\pi pt_y\right) \tag{54}$$

Such behavior would be noticed, for example, if the array of coils **306** is moved from y=-4.5 pitch to y=2.5 pitch.

Undesired torque resulting from x-y translation forces can be canceled using the following compensation function, which is the inverse sign of the equation used to calculate undesired torque:

$$T_{compensation} = 12k_a I_x \sin(\pi pt_y) \qquad (55)$$

where $T_{compensation}$ is the torque desired for compensation. The coil current required for the torque compensation is thus found (using the current term of Eq. 44 and the compensation torque of Eq. 45) as:

$$I_{t_{x(compensation)}} = \frac{T_{compensation}}{12k_a} = I_x \sin(\pi pt_y) \qquad (56)$$

where pt_y is the pitch in the y-direction. The torque control current is thus calculated as:

$$I_{t_x} = \frac{T_{desired}}{12k_a} + I_{t_{x(compensation)}} \qquad (57)$$

Using the undesired torque compensation function, control is decoupled between the translation force and the torque. Thus, exemplar outputs for the moving coil type planar motor of the present development with no force ripple and no torque ripple are shown in **Figs. 10** and **11**, respectively. In particular, as shown in **Fig. 10**, a plot of translational force (in Newtons) as a function of pitch (in number of pitch), the translation force is at a steady signal target of 70 Newtons. As shown in **Fig. 11**, a plot of the yaw torque (in Newton-pitch) as a function of pitch (number of pitch), the yaw torque is shown at a signal target of 50 Newton-pitch. The linear behavior demonstrates that the planar motor response meets the target behavior without force ripple.

Advantageously, the moving coil planar motor of the present invention does not require a switch function in order to achieve a desired torque at any given stage location because all of the commutation signal is matched in the sine and cosine math. While the force on a particular magnet in a moving magnet planar motor is not constant, thus necessitating switching in order to match pitch, a very constant force is experienced by the moving coil planar motor and thus no switching is required to match pitch.

Furthermore, only one amplifier is required per coil of the present invention. For example, as shown in equation 50, the commutation current for the coil located at position $(\mathbf{R_3}, \mathbf{C_1})$, which shall be designated hereafter as **CC1**, is given as:

$$CC1 = \begin{bmatrix} \left(I_x - I_{t_x}\right)\cos\left(x - 4\tfrac{\pi}{2}\right)\sin\left(y + 1\tfrac{\pi}{2}\right) + \\ \left(I_y - I_{t_y}\right)\cos\left(y + 1\tfrac{\pi}{2}\right)\sin\left(x - 4\tfrac{\pi}{2}\right) \end{bmatrix} \quad (58)$$

The output of the coil is converted to analog by a digital-to-analog **(D/A)** converter, and the analog signal is amplified with a power amplifier **AMP** before reaching the terminal of the coil. Such an arrangement is shown in **FIG. 12A**. Similarly, the commutation current of each other coil is converted and amplified using one amplifier per coil.

FIG. 12B is a block diagram of a position control system **350** using an exemplary array of sixteen coils **360** according to the present invention. A desired position target is input into a comparator **352**. The comparator **352** receives a feedback signal from sensor **354**. Controller **356** includes a transfer function **358** in series with a force and torque command module **360**. Currents i_x, i_y, for forces F_x, F_y, respectively, are supplied to commutation block **362**, which employs equations 48-51 to create a decoupling force and torque. Similarly, current components i_{tx} and i_{ty} from torque T_z are supplied to commutation block **362**. The commutation signals from coils **360** are then fed to sixteen amplifiers and the real magnet array **364**. Undesired torque compensators **366, 368** receive the position signal for compensation at position **354**. As should be appreciated by a person skilled in the art, sensor **354** is generic.

Fig. 13 is an elevational view, partially in section, showing a lithographic apparatus **400** incorporating a planar motor-driven positioning stage **402** in accordance with the present invention. Lithographic apparatus **400**, such as described in U.S. Pat. No. 5,528,118 to Lee, which is hereby incorporated by reference in its entirety, includes an upper optical system **404** and a lower wafer support and positioning system **406**. Optical system **404** includes an illuminator **408** containing a lamp **LMP**, such as a mercury vapor lamp, and an ellipsoidal mirror **EM** surrounding lamp **LMP**. Illuminator **408** also comprises an optical integrator, such as a fly's eye lens **FEL**, producing secondary light source images, and a condenser lens **CL** for illuminating a reticle (mask) **R** with uniform light flux. A mask holder **RST** holding mask or reticle **R** is mounted above a lens barrel **PL** of a projection optical system. A lens barrel **PL** is fixed on a part of a column assembly **410** which is supported on a plurality of rigid arms **412**, each mounted on the top portion of an

isolation pad or block system **414**. Lithographic apparatus **400** exposes a pattern of the reticle **R** onto a wafer **W**, while mask holder **RST** and positioning stage **402** are moving synchronously relative to illuminator **408**.

Inertial or seismic blocks **416** are located on the system, *e.g.* mounted on arms **412**. Blocks **416** can take the form of a cast box which can be filled with sand at the operation site to reduce the shipping weight of apparatus **400**. An object or positioning stage base **418** is supported from arms **412** by depending blocks **416** and depending bars **420** and horizontal bars **422**. Positioning stage **402** carrying wafer **W** is supported in a movable fashion by positioning stage base **418**. A reaction frame **424** carries a magnet array (not shown) and drives positioning stage **402** in cooperation with a moving coil array (not shown). Reaction frame **424** is isolated from positioning stage base **418** in terms of vibration relative to a foundation **426**, when a force is generated as positioning stage **402** is driven. Positioning stage **402** and/or mask holder **RST** according to the present invention can be driven by a planar motor such as planar motors **300** described above.

There are a number of different types of photolithographic devices. For example, exposure apparatus **400** can be used as a scanning type photolithography system which exposes the pattern from reticle **R** onto wafer **W** with reticle **R** and wafer **W** moving synchronously. In a scanning type lithographic device, reticle **R** is moved perpendicular to an optical axis of lens assembly **404** by reticle stage **RST** and wafer **W** is moved perpendicular to an optical axis of lens assembly **404** by wafer stage **402**. Scanning of reticle **R** and wafer **W** occurs while reticle **R** and wafer **W** are moving synchronously.

Alternately, exposure apparatus **400** can be a step-and-repeat type photolithography system that exposes reticle **R** while reticle **R** and wafer **W** are stationary. In the step and repeat process, wafer **W** is in a constant position relative to reticle **R** and lens assembly **404** during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer **W** is consecutively moved by wafer stage **402** perpendicular to the optical axis of lens assembly **404** so that the next field of semiconductor wafer **W** is brought into position relative to lens assembly **404** and reticle **R** for exposure. Following this process, the images on reticle **R** are sequentially exposed onto the fields of wafer **W** so that the next field of semiconductor wafer **W** is brought into position relative to lens assembly **404** and reticle **R**.

However, the use of exposure apparatus **400** provided herein is not limited to a photolithography system for semiconductor manufacturing. Exposure apparatus **400**, for example, can be used as an LCD photolithography system that exposes a liquid crystal display device pattern onto a rectangular glass plate or a photolithography system for

manufacturing a thin film magnetic head. Further, the present invention can also be applied to a proximity photolithography system that exposes a mask pattern by closely locating a mask and a substrate without the use of a lens assembly. Additionally, the present invention provided herein can be used in other devices, including other semiconductor processing equipment, machine tools, metal cutting machines, and inspection machines.

The illumination source **408** can be g-line (436 nm), i-line (365 nm), KrF excimer laser (248 nm), ArF excimer laser (193 nm) and F_2 laser (157 nm). Alternatively, illumination source **408** can also use charged particle beams such as x-ray and electron beams. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB_6) or tantalum (Ta) can be used as an electron gun. Furthermore, in the case where an electron beam is used, the structure could be such that either a mask is used or a pattern can be directly formed on a substrate without the use of a mask.

With respect to lens assembly **404**, when far ultra-violet rays such as the excimer laser are used, glass materials such as quartz and fluorite that transmit far ultra-violet rays are preferably used. When the F_2 type laser or x-ray is used, lens assembly **404** should preferably be either catadioptric or refractive (a reticle should also preferably be a reflective type), and when an electron beam is used, electron optics should preferably comprise electron lenses and deflectors. The optical path for the electron beams should be in a vacuum.

Also, with an exposure device that employs vacuum ultra-violet radiation (VUV of wavelength 200 nm or lower, use of the catadioptric type optical system can be considered. Examples of the catadioptric type of optical system include the disclosure Japan Patent Application Disclosure No. 8-171054 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,668,672, as well as Japan Patent Application Disclosure No. 10-20195 and its counterpart U.S. Patent No. 5,835,275. In these cases, the reflecting optical device can be a catadioptric optical system incorporating a beam splitter and concave mirror. Japan Patent Application Disclosure No. 8-334695 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377 as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart European Patent Application EP 0816892 A2 also use a reflecting-refracting type of optical system incorporating a concave mirror, etc., but without a beam splitter, and can also be employed with this invention. The disclosures in the above-mentioned U.S. patents, European patent application, as well as the Japan patent

applications published in the Official Gazette for Laid-Open Patent Applications are incorporated herein by reference.

Further, in photolithography systems, when linear motors (see U.S. Patent Nos. 5,623,853 or 5,528,118) are used in a wafer stage or a reticle stage, the linear motors can be either an air levitation type employing air bearings or a magnetic levitation type using Lorentz force or reactance force. Additionally, the stage could move along a guide, or it could be a guideless type stage which uses no guide. The disclosures in U.S. Patent Nos. 5,623,853 and 5,528,118 are incorporated herein by reference.

Alternatively, one of the stages could be driven by a planar motor, which drives the stage by electromagnetic force generated by a magnet unit having two-dimensionally arranged magnets and an armature coil unit having two-dimensionally arranged coils in facing positions. With this type of driving system, either one of the magnet unit or the armature coil unit is connected to the stage and the other unit is mounted on the moving plane side of the stage.

Movement of the stages as described above generates reaction forces which can affect performance of the photolithography system. Reaction forces generated by the wafer (substrate) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction forces generated by the reticle (mask) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224. The disclosures in U.S. Patent Nos. 5,528,118 and 5,874,820 and Japanese Patent Application Disclosure No. 8-330224 are incorporated herein by reference.

As described above, a photolithography system according to the above-described embodiments can be built by assembling various subsystems, including each element listed in the appended claims, in such a manner that prescribed mechanical accuracy, electrical accuracy and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, every optical system is adjusted to achieve its optical accuracy. Similarly, every mechanical system and every electrical system are adjusted to achieve their respective mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes mechanical interfaces, electrical circuit wiring connections and air pressure plumbing connections between each subsystem. Needless to say, there is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems. Once a

photolithography system is assembled using the various subsystems, total adjustment is performed to make sure that every accuracy is maintained in the complete photolithography system. Additionally, it is desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

Further, semiconductor devices can be fabricated using the above-described systems, by the process shown generally in **Fig. 14**. In step **501** the device's function and performance characteristics are designed. Next, in step **502**, a mask (reticle) having a pattern is designed according to the previous designing step, and in a parallel step **503**, a wafer is made from a silicon material. The mask pattern designed in step **502** is exposed onto the wafer from step **503** in step **504** by a photolithography system described hereinabove consistent with the principles of the present invention. In step **505** the semiconductor device is assembled (including the dicing process, bonding process and packaging process), and then finally the device is inspected in step **506**.

Fig. 15 illustrates a detailed flowchart example of the above-mentioned step **504** in the case of fabricating semiconductor devices. In step **511** (oxidation step), the wafer surface is oxidized. In step **512** (CVD step), an insulation film is formed on the wafer surface. In step **513** (electrode formation step), electrodes are formed on the wafer by vapor deposition. In step **514** (ion implantation step), ions are implanted in the wafer. The above-mentioned steps **511 -514** form the preprocessing steps for wafers during wafer processing, and selection is made at each step according to processing requirements.

At each stage of wafer processing, when the above-mentioned preprocessing steps have been completed, the following post-processing steps are implemented. During post-processing, initially, in step **515** (photoresist formation step), photoresist is applied to a wafer. Next, in step **516** (exposure step), the above-mentioned exposure device is used to transfer the circuit pattern of a mask (reticle) to a wafer. Then, in step **517** (developing step), the exposed wafer is developed, and in step **518** (etching step), parts other than residual photoresist (exposed material surface) are removed by etching. In step **519** (photoresist removal step), unnecessary photoresist remaining after etching is removed.

Multiple circuit patterns are formed by repetition of these preprocessing and post-processing steps.

It will be apparent to those skilled In the art that various modifications and variations can be made in the methods described, in the stage device, the control system, the material chosen for the present invention, and in construction of the photolithography systems as well as other aspects of the invention without departing from the scope or spirit of the invention.

While various descriptions of the present invention are described above, it should be understood that the various features can be used singly or in any combination thereof. Therefore, this invention is not to be limited to only the specifically preferred embodiments depicted herein.

Further, it should be understood that variations and modifications within the spirit and scope of the invention may occur to those skilled in the art to which the invention pertains. For example, magnet arrays and coil arrays having a different number of magnets and/or coils, respectively, from those discussed in detail herein may be used in accordance with the principles of the present invention. In one exemplary embodiment, with a stage stroke requirement of 10 pitch, the magnet area is selected to be at least two pitch greater than the stage stroke on each side of the stage. Accordingly, all expedient modifications readily attainable by one versed in the art from the disclosure set forth herein that are within the scope and spirit of the present invention are to be included as further embodiments of the present invention. The scope of the present invention is accordingly defined as set forth in the appended claims.